RADIO HALOS IN STAR FORMING GALAXIES

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Abstract We study the relation between radio halos, the energy input by supernovae in the disk and the galaxy mass. We find that both the energy input by supernovae as well as the galaxy mass are important parameters for understanding the formation of radio halos. Galaxies with a high energy input by supernovae per star forming area and a low galaxy mass generally possess radio halos whereas galaxies with the opposite characteristics do not. Furthermore, there is a tentative correlation between the observed scale height and the expected height in a simple gravitational approximation.

1. Introduction

There is accumulating observational evidence for the existence of gaseous halos around disk galaxies (see Dettmar 1992 and Dahlem 1997 for reviews), consisting of warm and hot ionized gas, dust, magnetic fields and cosmic rays (CRs), the latter two generating the radio continuum (synchrotron) emission. Theoretical models have been developed to explain these halos, such as the galactic fountain model (Shapiro & Fields 1976), galactic chimneys (Norman & Ikeuchi 1989), superwinds (Heckman et al. 1990) and superbubble outbreaks (MacLow & Ferrara 1999). All models are based on the assumption that the energy source driving the formation of halos are supernova (SN) explosions.

Observationally, it is still a matter of controversy how many and exactly which galaxies have such halos. In order to answer this question, we have been observing radio halos (Dahlem et al. 1995, Dahlem et al. 2001) in an ongoing project. In the present paper we summarize some results and use existing data to try to understand the formation of radio halos.

2. Observations of radio halos

Dahlem et al. (2001) observed a sample of galaxies with active star formation (SF) (selected with respect to the IRAS flux ratio between 60 and 100 μm,

$f_{60}/f_{100} \gtrsim 0.4$) with the VLA and the Australia Telescope Compact Array. They fitted the radio emission perpendicular to the disk with two exponential functions convolved with the beam, modeling in this way a thin disk and a halo. Radio halos were found in 6 out of 11 galaxies (55%) with exponential scale heights between 1.4 and 3.1 kpc. The high detection rate in these actively star forming galaxies showed that SF is indeed a key factor for the formation of radio halos. Possible reasons for the non-detection of halos in 5 galaxies could be: (i) There is no radio halo. (ii) The resolution of the data is too low. We are currently obtaining higher resolution data for some objects. (iii) The width of the thin disk is much smaller than the beam and therefore not resolved. This is supported by the fact that for galaxies with no radio halo the apparent scale height of the thin disk was much larger (between 1 and 2 kpc) than in galaxies with a radio halo (less than 1 kpc).

In order to base our present study on a larger number of galaxies, we use, in addition to the 11 galaxies from Dahlem et al. (2001), data for 6 galaxies described in Dahlem et al. (1995), as well as for 3 galaxies from Irwin et al. (1999) who observed 16 edge-on galaxies searching for radio halos. Their analysis of the radio emission is different from ours and involves a ranking of the visibility of extended emission based on different criteria. We include only those galaxies for which their VLA D-array data does not show evidence of emission beyond their modelled thin disk (their Fig. 1), a robust criterion that is similar to the one used in the rest of the sample.

3. Understanding radio halos

From theoretical considerations we expect that the formation of radio halos depends (at least) on the following factors.

1) According to all models (see above) a fundamental parameter is the energy input by SN explosions into the interstellar medium. Dahlem et al. (1995) showed that radio halos do not form above the entire disk, but only out to radial distances where SF takes place. Therefore, the relevant parameter is expected to be the energy input by SNe per SF disk area, $\dot{E}/A_{\rm SF}$.

2) The energy input from SNe allows material to be lifted above the disk against the gravitational potential determined by the mass of the galaxy. Therefore, the mass of the galaxy is expected to play an important role.

3) CR electrons have a limited life-time due to inverse Compton and synchrotron energy losses. The observed steepening of the synchrotron spectrum with increasing distance from the disk (e.g. Hummel et al. 1991) is due to these energy losses and shows that they are indeed important. These energy losses limit the distance to which CR electrons can travel and therefore the size of radio halos. In the present work, we do not take into account CR energy losses, because it would require a detailed knowledge of the distribution of the

energy density of the radiation field, $U_{\rm rad}$, (determining the inverse Compton losses) and the magnetic field structure (causing the synchrotron losses and emission and determining the CR propagation). Qualitatively, we expect CR energy losses to decrease the range of observed scale heights because galaxies with a high surface brightness (implying a high SF rate and thus a high $\dot{E}/A_{\rm SF}$) also possess a high $U_{\rm rad}$ causing important inverse Compton losses.

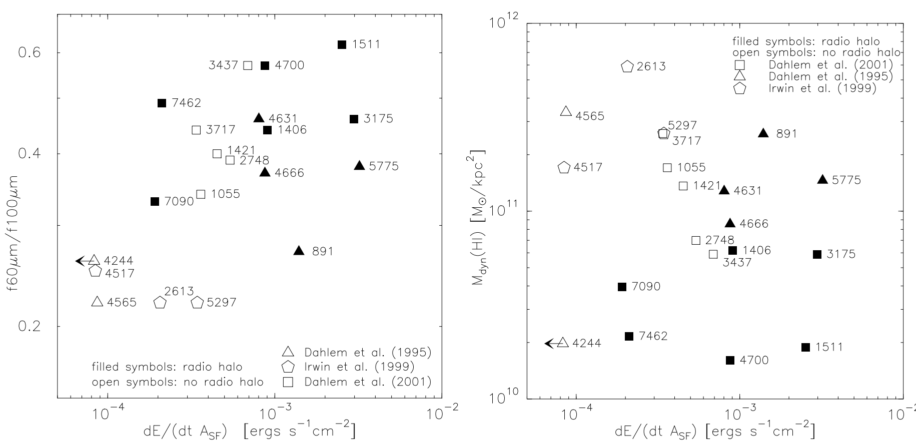

Figure 1. The energy input by SNe per SF area as a function of the IRAS flux ratio between 60 and 100 μm, f_{60}/f_{100} **(left)**, and the dynamical mass of a galaxy, $M_{\rm dyn}$(HI), calculated from the HI linewidth **(right)**. As a measure for the energy input by SNe we use the radio continuum emission as described in Dahlem et al. (1995).

Fig. 1 (left) shows the dust temperature (measured as f_{60}/f_{100}), which is an empirical measure for the SF activity, as a function of the energy input by SNe per SF area. There is a rough correlation between both quantities and a trend for radio halos to be found in galaxies with a high dust temperature, respectively a high $\dot{E}/A_{\rm SF}$. A similar conclusion was drawn from the smaller sample used in Dahlem et al. (2001) and by Rossa & Dettmar (2003) for a sample of 74 edge-on galaxies observed in Hα.

Fig. 1 (right) shows $\dot{E}/A_{\rm SF}$ versus the dynamical mass of a galaxy. There is a clear division between galaxies with and without a halo: Galaxies with a low mass and a high energy input (lower right side) have radio halos whereas galaxies with a high mass and a low energy input (upper left side) do not. This shows that the galaxy mass plays an important role in the formation of radio halos.

Fig. 2 shows the observed exponential scale heights of the radio emission versus the expected height in the simple approximation that the energy input per mass is proportional to $\dot{E}/A_{\rm SF}$, that energy losses of CR electrons are neglected and that the gravitational potential is described by that of an infinite disk. With these assumptions, the expected height of the radio halo is pro-

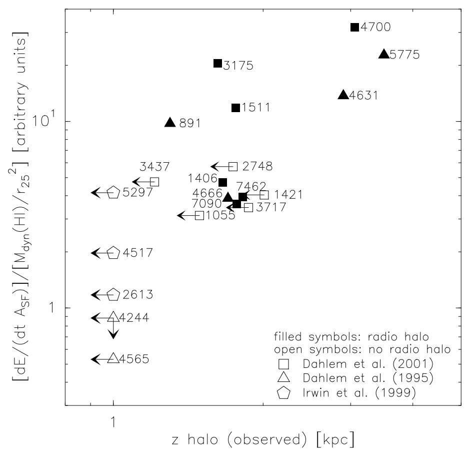

Figure 2. The observed exponential scale height of the radio halos versus the expected height in the approximation described in the text. For the galaxies without a detected radio halo from Irwin et al. (1999) and Dahlem et al. (1995) we adopted an arbitrary but realistic upper limit of 1 kpc. For the galaxies from Dahlem et al. (2001) without a detected radio halo we adopted the measured scale height of the thin disk as an upper limit.

portional to $\dot{E}/A_{\rm SF}$ per mass surface density. A trend is visible in the sense that large radio halos are present in galaxies with high values of $(\dot{E}/A_{\rm SF})$ per mass surface density whereas galaxies with no radio halos have a low values. This indicates that – although more detailed modelling taking into account CR propagation is necessary for a full understanding – the energy input by SNe and the galaxy mass are important parameters to understand the properties of radio halos.

Acknowledgments

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